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AGARD REPORT No. 667

Combat Damage Tolerance and Repair of Aircraft Structures

NORTH ATLANTIC TREATY ORGANIZATION

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PREFACE

The Structures and Materials Panel of AGARD has for some time been active in the field of impact damage tolerance of structures and this work has included the holding of a Specialists' Meeting in Ankara in September 1975 (see AGARD Conference Proceedings CP – 186) together with the publication of several reports. The work will culminate on the publication of a Design Manual in 1979. This Manual will describe the methodology which exists both to determine the damage resulting from the impact of various types of projectile, including military projectiles and non-contained engine debris, and also to determine the resulting capabilities of the damaged structure. This should aid the designer in making assessments of the tolerance of the structure to various threats and the probability of the aircraft surviving the impact, completing the mission and returning safely to base.

However, this covers only part of the problem of maintaining an adequate defence capability. An aircraft is still 'lost' as an effective part of the air force if it proves impossible to repair the damage quickly, particularly in the context of a short-duration conflict. Vitally important are the methods of rapid inspection and assessment of the damage to determine the extent of repair required or if repair may safely be deferred. Thus, the total number of aircraft required to meet a given military situation is determined at least in part by their combat damage tolerance and repair characteristics; improvements in these characteristics can produce real reductions in defence costs.

The Panel reviewed these questions at its meeting in Aalborg, Denmark, in April 1978. Three papers were presented, and are reproduced here, giving an overview of the present situation and directing attention to the areas most needing further work.

N.F.HARPUR
Chairman
Structures & Materials Panel

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APPROACHES TO COMBAT DAMAGE REPAIR

by

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SUMMARY

This paper discusses the issues of maintaining helicopters under mid-intensity combat conditions. The need to defer all but essential scheduled and unscheduled maintenance is addressed, with specific interest directed toward minimizing aircraft downtime for combat damage repair. It is apparent that the application of interim, quick-fix approaches for certain combat damage repair is needed to achieve an optimum combat maintenance capability. Selected damage repair techniques are discussed; requirements for further development in this area are also addressed.

INTRODUCTION

Considerable effort has been expended in determining vulnerability characteristics of Army helicopters; an even greater effort has been directed toward decreasing the overall vulnerability of these systems. It is obvious, however, that although substantial improvements in survivability can be achieved, there will be a need for extensive repair when an aircraft has been subjected to combat damage. Most survivability analyses examine the probability of continued operation following damage for a designated period of time (30 minutes, for example). Such a capability is thought to provide adequate protection for safe return to a friendly site; when this occurs, the aircraft is considered "saved." A total operational analysis for mid-intensity combat will show, however, that if the damaged aircraft cannot be returned to a serviceable condition within a very short period of time (8 hours, for example), the aircraft will most likely be lost. This occurs due to mobility requirements of the modern battlefield and the unacceptable logistics problems associated with moving nonoperational helicopters.

Recognition of the above has led to an increased concern and emphasis on combat damage repair for Army helicopters. This paper discusses the pertinent issues impacting an overall concept for combat maintenance with specific emphasis on approaches to achieving repair of combat damage.

MAINTENANCE DURING COMBAT

Figure 1 presents the types of maintenance downtime which occur during either peacetime or periods of combat operation (recognizing, of course, that combat damage repair does not occur in peacetime). During peacetime operations, emphasis is placed on scheduled maintenance, with overall flight safety objectives dominating the selection of a preferred maintenance support concept. Many components have rather conservative operating lives assigned or scheduled overhauls dictated which minimize the potential of catastrophic failures. Scheduled inspections are also utilized to further reduce the potential for catastrophic accidents. Unscheduled maintenance during peacetime is normally accomplished as soon after a failure occurs as possible, regardless of the seriousness of the failure.

Combat maintenance, on the other hand, is geared to keeping all aircraft in a basic operational condition with a minimum investment of maintenance downtime. Emphasis is placed on deferring all but essential maintenance during the combat period. This usually means that scheduled maintenance is substantially decreased and the preponderance of downtime will be for essential unscheduled maintenance actions. Figure 2 graphically depicts the distributions in maintenance downtime for peacetime and combat operations. Although Figure 2 is nondimensional, the general relationships of scheduled, unscheduled and combat damage repair are felt to be realistic. The impact of combat damage repair on total aircraft downtime is quite apparent, and it is easy to see why this has become an area worthy of extensive investigations.

The Army has initiated research investigations which are expected to result in concepts and approaches that minimize maintenance downtime during combat for all reasons (scheduled and unscheduled). Generally, the concept for scheduled maintenance would be to establish a peacetime inspection and time-based maintenance program which is arranged to allow "surge" flying (up to 300 hours in 1 month) with virtually no inspections or other time-based maintenance required. This means that component retirement (fatigue) lives must be critically examined to determine the risks associated with continued operation beyond the finite operating period; similarly, component scheduled overhaul

requirements must be assessed to determine safety risks for operating well beyond the prescribed removal point. Unscheduled maintenance requirements will be examined to determine if a relaxed criteria for "downing" an aircraft can be accepted during periods of combat. Typically, the number of broken strands which forces a *flight control cable* replacement in peacetime might be increased significantly during combat; unacceptable leak rates of hydraulic systems and lubricating oil consumption rates for engines and gearboxes during peacetime may be fully acceptable (as opposed to component replacement) during combat. Once the absolute minimum downtime has been reached for scheduled and normal unscheduled maintenance, the full impact of improved combat repair techniques can be realized. The reader is cautioned, however, that a total maintenance approach is required to realize the maximum benefit from any specific maintenance improvement. The remainder of this paper will deal solely with combat damage maintenance/repair.

THREAT CONSIDERATIONS AND SURVIVABILITY

All potential ballistic threats can be placed in either of two major categories: explosive or nonexplosive. Furthermore, it becomes immediately apparent that component repair (as opposed to replacement) following damage by an explosive round is rather unlikely. Figure 3 depicts a helicopter tail boom which was hit with a 23mm nonexplosive round; this left a sizeable but potentially repairable hole. Figure 4, however, demonstrates that the same tail boom hit with a 23mm high explosive incendiary (HEI) round is clearly not repairable; in fact, there is some question that damage such as this is even survivable. The above comments point out that it is not worthwhile to consider development of repair concepts/techniques for all potential combat damage. Emphasis should be placed on repair of damage expected from nonexplosive rounds where the damage is insufficient to cause catastrophic loss of the helicopter but sufficient to require corrective maintenance prior to another mission; this is, admittedly, a "motherhood" statement, but there are definite opportunities to apply such a theory.

The first step in evaluating repair alternatives is to determine which components have a high probability of noncatastrophic combat damage but will require corrective maintenance prior to further utilization. Such an analysis was recently completed for US Army AH-1 series helicopters and resulted in the ranking as shown in Table 1. The most likely hit for both 12.7 and 23mm armor piercing type threats was established; Table 1 also provides a ranking of the components' potential to cause a forced landing following damage by the specified threat. The ballistic damage information provided in Table 1 was developed through use of a vulnerability model which examines relative presented areas of the various components; subsequently, the damage tolerance of each component is combined with the probability of being hit to establish a vulnerability ranking. Although this technique represents something less than a full survivability analysis, it is sufficient to identify relative payoff potential for component combat damage repair.

Table 1. COMBAT BALLISTIC DAMAGE REPAIR/DEFER CANDIDATES

(Threat 12.7 API except as noted)

Component	Most Likely Hit	Forced Landing Ranking*
Main Rotor Blade	1	0
Tail Rotor Drive Shaft	2	1
Tail Rotor Blade	3	0
Fuel Cell (Leak)	4	0
Hot Section (Engine)	5	2
Rods - Tail Rotor Flight Control	6	9
Compressor (Engine)	7	7
Transmission - Lube	8	3
Non-Airframe Lines - Engine	9	4
Oil Tank - Engine	10	8
Gearboxes - Engine	11	10 (23 mm API)
Rod Ends - Tail Rotor Flight Control	12	5
High-Pressure Fuel (Leak)	13	10
Cables - Tail Rotor Flight Control	14	6
Main Rotor Head	6	Attrition ranking

* 1 - Most Likely

0 - Very Low Probability of Forced Landing

It is clear from Table 1 that a large number of components fall into the category of high probability of hit but also have a very low probability of causing aircraft loss. It is equally apparent that some of these components do not represent reasonable candidates for field level repair; for example, it is unrealistic to consider repair of an engine compressor housing. It was determined at this point that a review of Army experience with combat damage as seen in Southeast Asia could provide valuable information on practical limitations and alternatives for damage repair. Consequently, a field survey was conducted to collect Army helicopter maintenance personnel opinions on practical considerations for combat damage repair. The principal area of concern in the survey was determination of which components the maintenance personnel felt represented the greatest potential for field repair; Table 2 provides the results of the survey. It is interesting to note that the title of Table 2 relates to defer/quick-fix/interim-fix alternatives. The field maintenance personnel strongly feel that inspection criteria for assessing combat damage are rather limited and should be examined/developed; once completed, the criteria may very well result in a considerably higher percentage of combat damage repairs being deferred.

The components identified in Table 2 are ranked rather high in "probability-of-hit" (Table 1), and each will require repair prior to flight release. Furthermore, all of these components have a reasonable potential for field level interim repair. Finally, field maintenance personnel pointed out that these components will most likely be difficult to obtain during periods of combat; this occurs because large quantities of spares for these components are not normally stocked at the user level.

Results of the analytical assessments and field surveys have been reviewed in some detail, and it appears that research and development efforts would support development of combat damage repair capability in the following areas:

- Rotor blades
- Fluid lines
- Tail rotor drive shafts
- Push-pull tubes
- Tail boom longerons
- Structural panels
- Gearbox housings/cases

The remainder of this paper will discuss objectives and developments to date in these areas.

Table 2. TOP 10 DEFER/QUICK-FIX/INTERIM-FIX ITEMS DESIRED FROM THE FIELD

Fuel/hydraulic/oil lines	64%
Push-pull tubes	38%
Fuel cells	23%
Rotor blades	23%
Tail rotor drive shafts	23%
Structural repair (tail boom longerons, stress panels, sheet metal)	15%
Pitch change links	13%
Gearbox casings	13%
Repair kit (tape)	13%
Canopy glass	10%

COMPONENT REPAIR APPROACHES

Before discussing the potential repair approaches for the components identified above, some comment regarding qualitative features is in order. First, the ability to rapidly inspect and determine the appropriate maintenance action required is an essential ingredient to an effective combat maintenance program. The deference of repair will always be the desired option for dealing with combat damage. It is therefore essential that the field maintenance personnel be provided readily usable combat damage inspection procedures. This requires extensive analytical assessments supported by tests to establish damage limits for all critical components. Damage limits should be presented to field maintenance personnel in pictorial fashion supported by simple language.

The second major qualitative feature deals with repair materials/kits requirements. Generally, no repair system will have much effect if it cannot be issued and stocked at the user level. Operational effectiveness with regard to combat damage maintenance will relate almost one-to-one with total maintenance downtime. If a user unit must depend on a higher maintenance level for supplying repair materials/kits, most of the effectiveness

advantages available through repair (versus replace) will be lost. Therefore, certain overall qualitative design features should be considered:

Size and mobility: Materials and kits must be readily moved by the user organization with no special consideration regarding packing and storage.

Shelf life: Useful life of years must be achievable. The need to replace kits/materials annually, for example, is logistically unacceptable.

Storage: No special storage requirements (environmental control) can be accepted; this, of course, precludes use of certain adhesive materials.

Environmental effects: Obviously, the repair should be possible under all environmental conditions.

Skills required: The repair should be self-explanatory; this means repair kits should contain simple, straightforward instructions and eliminate the need for specially trained personnel.

Quality control: Special equipment for quality control (NDE/NDI) should not be required. It is desired that simple visual checks be the extent of inspection required.

Now, let's review the repair approaches available for the components in question.

Rotor Blades

Helicopter operations in Southeast Asia clearly demonstrated that rotor blades can receive extensive ballistic hits even under low-intensity combat conditions. Most of the damage came from small arms (14.7mm and less), and it is interesting to note that the damage was randomly distributed over the entire blade area. The damage distribution is important because it offers insight into the types of repairs which may be required if field repair is considered.

Field level repair of rotor blades has traditionally been limited to patching of surface damage and "blending out" dents and scratches in noncritical areas. Repair of spar damage is not considered a viable option at depot or field level. Recently, however, an Army R&D program for evaluation of rotor blade repair techniques has provided some hope for improved expanded field repair. Figure 5 schematically depicts the concept in question which consists of the following steps:

1. First, damage is considered field repairable only if it occurs in the nonspar area; i.e., aft body. Most current and proposed rotor blades utilize an aft body made up of a honeycomb core of either Nomex or aluminum and a skin of either fiberglass or aluminum. When ballistic damage occurs, the maintenance personnel inspect the blade to insure that damage to the spar has not occurred; that the afterbody damage is within the size limitations of repair kit plugs and patches; and that sufficient blade weight adjustment is available to accomplish balance for a given repair.

2. Blade afterbody damage of major consequence is removed by routing a cylindrical cavity over the damaged area. A template is centered over the damage and secured to the blade. The circular guide holes of the template guide and the interchangeable stop knobs on the router wings insure a cylindrical cavity of proper size. The template is then removed and the routed cavity is cleared of foreign debris.

3. The repair kit contains a presized plug consisting of a Nomex honeycomb cylinder and a fiberglass skin, a wafer of the same size as the plug, and miscellaneous expendable items. Both the wafer and underside of the plug skin are coated with adhesive material.

4. The wafer and plug are fitted into the hole and a pressure-heat pack is secured to the blade. Aircraft electrical power provides for heating, and a hand-operated pump is used to apply pressure. Approximately 15 minutes is required to achieve a satisfactory bond. Light sanding of adhesive squeeze-out along the edge of the patched area is accomplished after the pressure-heat pack is removed.

5. The operation is then repeated from the opposite side of the blade; this usually means that a portion of the first patch will be cut away with the router and a completed repair will appear as shown in Figure 6.

The blade field repair concept has been demonstrated on both nonmetallic and metallic skin configurations. A full flightworthy repair can be completed on a UH-1 type helicopter in under 3 hours by personnel who have had only minimal instruction in blade repair practices. A formula is provided to instruct the repairman on change in tip weight that may be required to maintain proper weight and balance. It should be pointed out here that replacement of a blade requires approximately 3 hours; consequently, the blade repair becomes a viable option for the field commander. It takes no more time than blade replacement.

It is envisioned that field repair kits containing all materials essential for one or more blade repairs would be available at each operating unit. This provides added incentives for blade repair versus replacement, since a replacement blade must be obtained from a higher maintenance level which greatly increases the total downtime. Shelf life of

the repair kit is of no major concern; however, it now appears that separate packaging of the adhesive ingredients can provide a reasonable useful life.

Spar damage is currently considered nonrepairable at any maintenance level. This situation exists primarily due to the poor notch sensitivity of metal spars used in most operational blades; furthermore, it is highly unlikely that repair of metal spars will ever become a realistic alternative. There is a move, however, toward the use of nonmetallic blade spars which offers improved damage tolerance and some options in field level repair. Most nonmetallic composite blade spar configurations are designed to accommodate quasi-automatic manufacturing, which normally means that a constant spar cross section is produced; however, the cross section dimensions are selected to accommodate stiffness requirements at the points of maximum bending moment. This results in a design which has considerably greater strength than actually required at most points along the spar. Consequently, it is realistic to expect that much of the small arms damage to these spars will not be critical and a simple "cosmetic" type patch for aerodynamic smoothing and environmental protection will suffice. There is a need for certain test and evaluation efforts to confirm the precise damage limits; subsequently, a suitable set of inspection criteria can be developed for use by field maintenance personnel.

Fluid Lines

Flexible and rigid (steel, copper, aluminum, etc.) fluid lines are utilized throughout the helicopter and are expected to be subjected to significant combat damage. Two basic alternatives are available for the rapid repair of these lines: replacement of the damaged section and patching of the line at the point of damage. Currently, the Army allows limited repair of low pressure (less than 100 psi) rigid lines by removal of the damaged area and replacement by a rigid section held in place by flexible hose sections and clamps (Figure 7). This concept is considered potentially usable for high pressure systems (3,000 psi) through utilization of special configured tubing, hose and clamp assemblies. Unfortunately, such assemblies are not currently available and represent one objective of the Army's ongoing combat damage repair technology program. The risk of achieving a satisfactory rigid line repair capability is considered low.

Indirect hits and damage due to rounds grazing rigid lines result in a very small leak point that currently requires replacement of the damaged section. If a high-strength, fluid-resistant tape were available, interim repair of this type damage could be achieved by simply wrapping the tape over the damaged area. Although such a tape has not been identified at this time, it is felt that a combination of materials and adhesives can be obtained to fulfill the requirement envisioned. Once developed, the tape is expected to have additional combat damage repair value, which is discussed in more detail later in this paper.

Repair of flexible fluid lines appears to be limited to replacement of the damaged section. One quick-fix alternative would be the removal of a few inches of lines containing the damaged area and the insertion of conventional and fittings which could be joined by a union fitting. The application of structural tape to flexible lines is not considered a viable alternative.

Tail Rotor Drive Shaft

These shafts are expected to experience both direct hits and secondary ballistic damage. The principal issue surrounding quick-fix repair is the absolute requirement for maintaining dynamic stability. The first major issue is development of damage assessment criteria; specifically, when is a repair/replacement required? If a repair is required, the most promising concept available is the utilization of "clamshell" pieces clamped over the damaged area (Figure 8). In some cases, it may be necessary to remove the damaged section and use the "clamshell" as an actual portion of the shaft.

The above repair concept has not been evaluated, and it is expected that many variations of the concept will be possible. Typically, the repair may be utilized in some instances to support a one-time flight; in other cases, it may be suitable as a quasi-permanent repair.

Although mechanical clamps are shown in Figure 8, the tail rotor repair concept would benefit greatly from the development/utilization of the structural tape mentioned in the fluid line repair discussion.

Push-pull Tubes

These components are similar in design to the tail rotor drive shafts and are expected to see the same type damage. Fortunately, however, the push-pull tubes represent a very minor problem with respect to dynamic balancing; therefore, extensive utilization of the repair concept described for tail rotor drive shaft should be possible.

Tail Boom Longerons

Repair of tail boom longerons is quite limited today due to the difficulty in achieving access to the internal structure. The basic repair concept envisioned here is the use of an externally applied longeron which bridges the damaged area. Although such a repair is aesthetically degrading, it will have a minor impact on aircraft aerodynamic characteristics. It is expected that the repair will require only minutes

to accomplish and will consist of the following steps:

Select the required longeron length.

Utilize the replacement longeron as a template for drilling on either side of the damaged area.

Install the replacement longeron using standard blind rivets.

Fortunately, most tail booms utilize a great number of longerons; consequently, the criticality associated with a single repair is very small. Actual testing is needed to determine the extent of repairs that could be accomplished on any one tail boom.

Structural Panels

Most structural panels in use today utilize sandwich construction (skin-honeycomb-skin). Consequently, a repair concept similar to that developed for the aft body of rotor blades should have application potential for structural panels. The requirement of heat-pressure packs for these repairs significantly restricts overall application; consequently, effort is needed to develop approaches that simplify the repair process and reduce dependency on external heat sources. Development of an effective repair technique for structural panels should permit repair of substantially larger areas than currently allowed, thereby greatly reducing the total number of spare panels required.

The availability of a structural tape such as described earlier will greatly assist in structural panel repair; specifically, surface damages could be repaired by simply placing a section of tape over the damaged area. This type repair is very important due to the environmental protection provided to the honeycomb material.

Transmission and Gearbox Casings and Sumps

These components are expected to experience frequent superficial damage that will, unfortunately, require component replacement; specifically, a small hole in a casing or sump causes loss of lubricant which cannot be tolerated. It is felt that a simple flexible plastic material which can be hand-pressed into holes in the casing will prevent many unnecessary component replacements. Strict criteria for determination of repair versus replacement will be required when considering casing damage; the point here is that metal fragments resulting from damage may cause secondary (catastrophic ?) damage to internal gears and bearings. It is generally thought that only damage due to grazing and secondary (glancing) hits would be considered field repairable.

Sumps, however, are noncritical areas and should be repaired to the maximum extent possible. Either structural tape or a plastic material such as described above are viable candidates for achieving sump repairs.

FUTURE CONSIDERATIONS

The emergence of composite materials/structures is causing a widespread interest in their application to helicopters. As these considerations develop, it is essential that the potential for combat damage repair be assessed and the final design decision be directed at minimizing maintenance difficulties. It is essential that ongoing and future R&D efforts related to the development and application of composite materials/structures consider the issues with respect to combat damage repair methodology. Three such areas to consider are described below (quoted directly from reference).

Utilization of Weight Savings

If a significant weight savings can be achieved through composite structures, serious consideration should be given to "reinvestment" of the savings into improved deferrability of combat damage maintenance. The worth of such an approach can only be assessed by careful analytical assessments supported by experimental investigations. This situation is similar to that encountered in the recent application of finite element analysis techniques to metal airframe design. Specifically, advanced design analysis approaches provided optimized arrangements which yielded considerable weight savings; it was later determined, however, that the weight savings could be put to good use in meeting crash survivability objectives. Consequently, the aircraft empty weight remained about the same, but a desired operational characteristic was achieved. The development of design criteria and related weight/cost changes for achieving various safe operating periods will require a major R&D investment, but the resultant benefits may very well be the deciding issue in accepting wide usage of composite structures.

Large Area Repair Considerations

During the early composite structures design concept formulation stages for Army helicopters, the issue of large area repair in the field must be considered. General design arrangements (unitized body versus multiple sections) and/or the reduction in number and types of joints and fittings will subsequently dictate the repair capability required in the field. Additionally, requirements for spares and equipment needs will subsequently impact on the Army's maintenance concept, and operational costs will result from these decisions.

Field Repair

Interim repairs for nondeferrable maintenance offer improved operational availability; however, such repairs must be accomplished under very austere, trying conditions. Definition of quality control (inspection) for insuring that interim repairs are successfully completed must be available and easily imposed. It is apparent that interim fixes of secondary structures will be more readily achievable than for primary elements. R&D investigation should recognize such differences and insure that the critical repairs receive maximum attention.

CONCLUSIONS

Operational availability during combat operations will be greatly enhanced with the implementation of an overall combat maintenance support program. This implementation cannot be achieved by doctrine alone. A systematic approach must be taken to consider combat maintenance support methodology from the initial design to the operational phase of an aircraft system. An extensive R&D program is required to examine such issues as increased retirement lives, repair versus replacement decisions, deferrability criteria, and quick- and interim-fix capabilities to assess the risks and benefits that will be achieved. It is felt that the results of such a program will have a significant impact on the operational effectiveness of current and future Army aircraft.

REFERENCE

House, Thomas L., and Condon, Thomas E., "Impact of Operational Issues on Design of Advanced Composite Structures for Army Helicopters," presented at the AHS/NASA/Ames Conference on Helicopter Structures Technology at Moffett Field, California, 16-18 November 1977.

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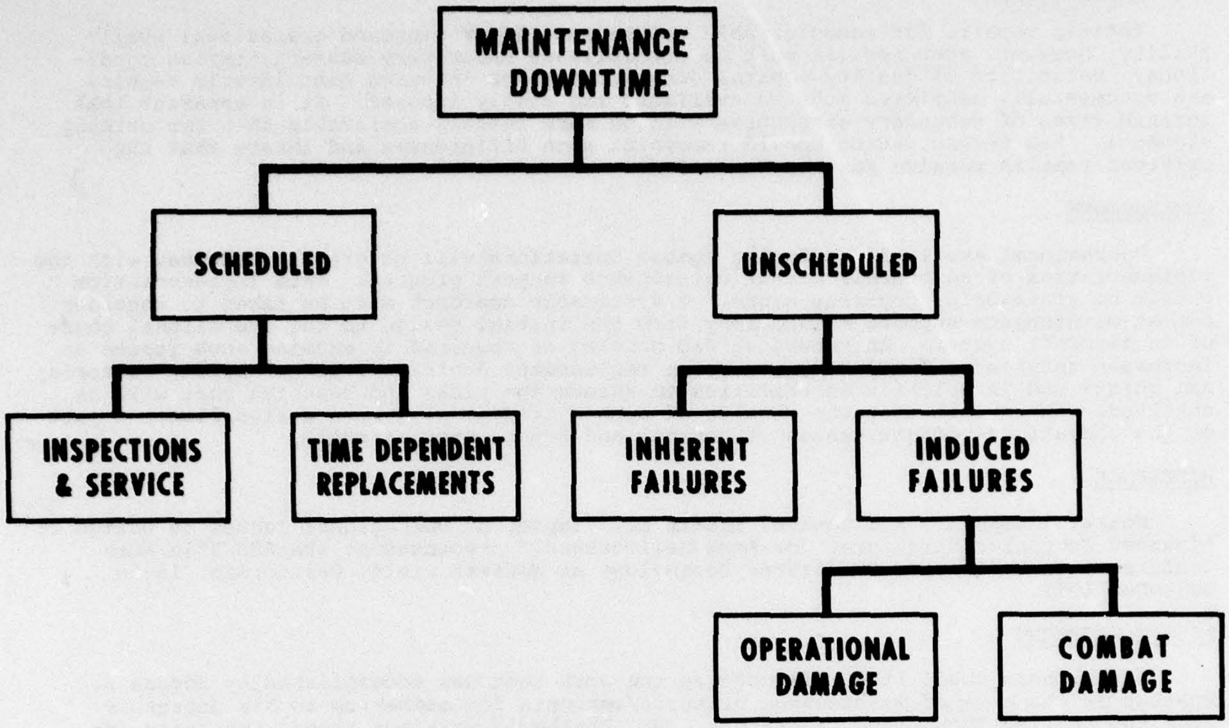

Figure 1. TYPES OF MAINTENANCE DOWNTIME

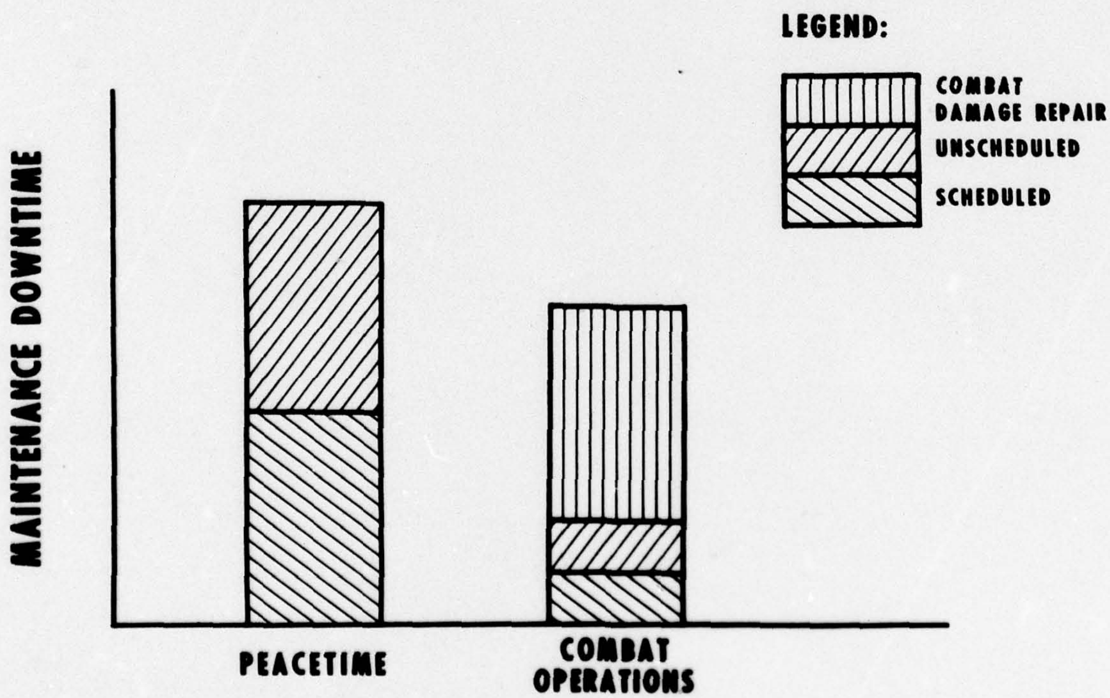

Figure 2. DISTRIBUTION OF MAINTENANCE DOWNTIME

Figure 3. TAIL BOOM HIT WITH NONEXPLOSIVE ROUND

Figure 4. TAIL BOOM HIT WITH EXPLOSIVE ROUND

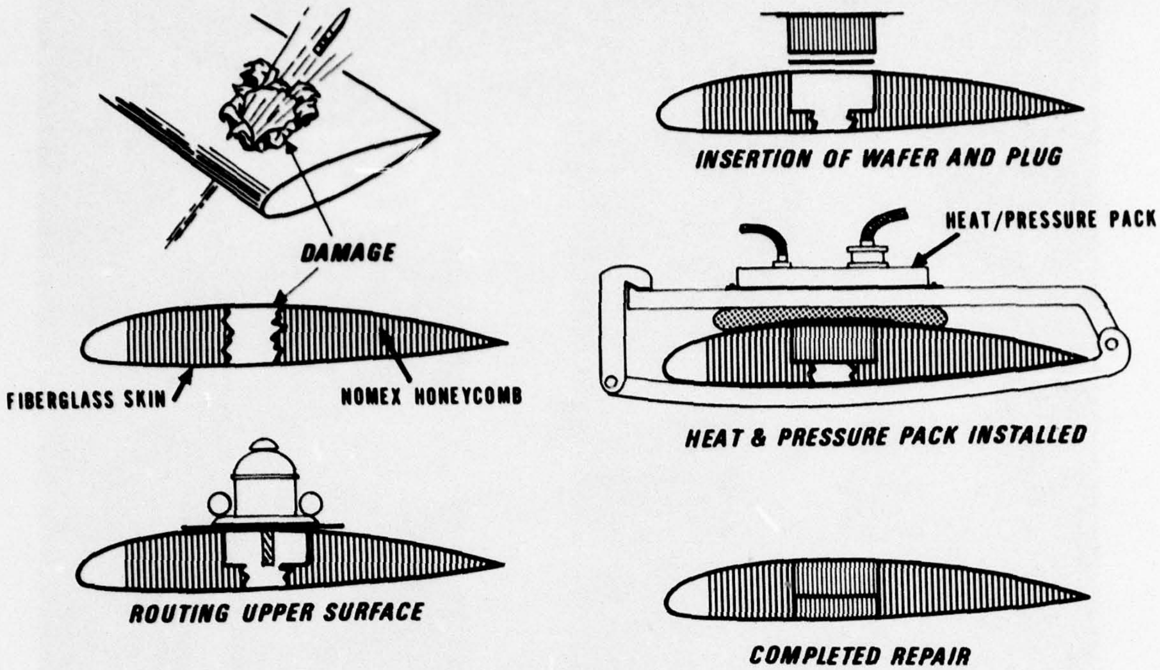

Figure 5. REPAIR PROCEDURE FOR THE FIELD REPAIRABLE MAIN ROTOR BLADE

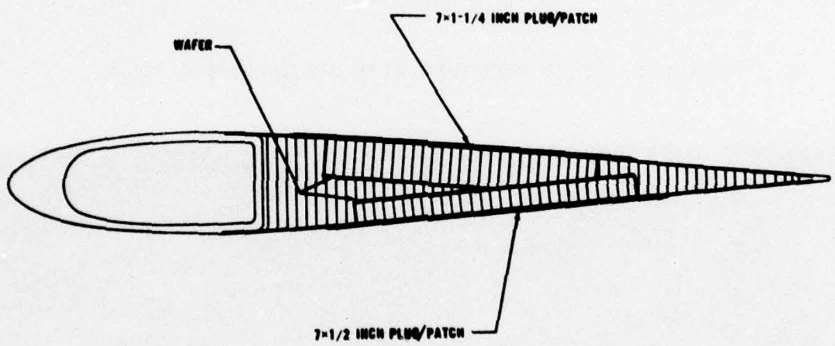

Figure 6. TYPICAL DOUBLE PLUG PATCH REPAIR

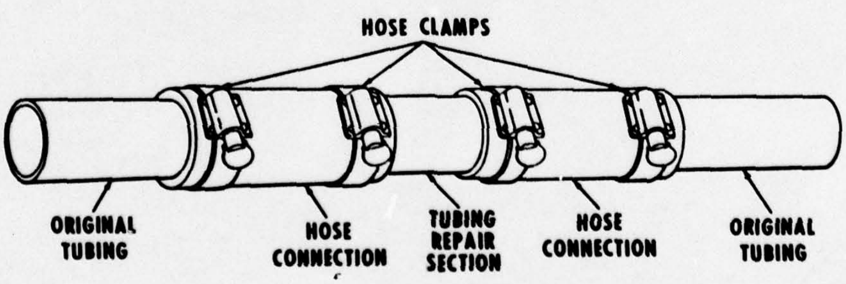

Figure 7. RIGID LINE REPAIR

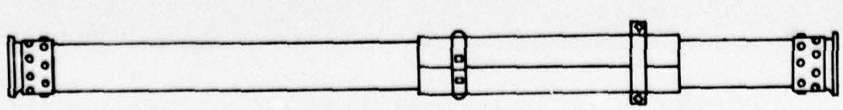

Figure 8. TAIL ROTOR DRIVE SHAFT REPAIR

SOME CONSIDERATIONS OF THE LIKELY TOLERANCE TO, AND REPAIR OF, BATTLE DAMAGE IN COMBAT AIRCRAFT STRUCTURES

by

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SUMMARY

After outlining the design cases and likely margins of strength on the major structural components of typical combat aircraft, the paper deals with the levels of allowable damage which may be expected for both sharp-edged and cleaned-out holes caused by projectile damage to structural skins.

Simple skin repairs are then discussed, followed by a suggested format for a structural Battle Damage Manual.

1. INTRODUCTION

It has been postulated that about 10% of combat aircraft attrition has been caused by structural failures induced by projectile damage. Whilst recognising that for future aircraft design, damage tolerance considerations will have to be part of the structural design process, the problem remains with the aircraft currently in service which have not been designed to withstand battle damage, and which may sustain damage in times of war. This report relates to the structure of typical modern combat aircraft and deals briefly with aspects which will require consideration by the designers in order to produce information for Service personnel for a Battle Damage Manual. The likely tolerance to battle damage, in the first instance containing sharp edges and then the effect of subsequent cleaning-out, is considered, giving some guide to an aircraft's capability to carry out further operations without repair. Finally, methods of quick repair, which can be carried out by Service personnel, are outlined and a simple method of presentation for the Service engineers is offered.

It is not the purpose of this report to discuss either the threat or the damage likely to be sustained by the aircraft structure but, clearly, some estimates have to be made of expected levels to be considered by the designer before he can give the necessary advice. To this end, it is recommended that consideration be given to conducting firing trials on actual parts of structures, possibly with the structure under simulated flight loads.

2. CONSIDERATIONS WHICH MAY AFFECT THE FLIGHT CLEARANCE OF DAMAGED AIRCRAFT

An airframe is designed for a wide range of conditions, covering many types of sorties and configurations. If the assumption is made that there are little or no margins of strength and that the full design envelope is to be covered at all times, then, clearly it will always be necessary to repair damage to the aircraft structure.

In reality, some parts of the structure may have margins of strength (because of stiffness design, or fatigue requirements, for example), and the particular operational requirements may be such that the loads are less severe than for the design cases.

The following sub-paragraphs deal briefly with the design cases and likely strength margins of typical main structural components.

2.1 Wing Structure

Apart from local inputs from the various control surfaces, the main design case for wing structures is a low-level, high 'g' symmetric manoeuvre. Consideration of a reduced 'g' coupled with a minimum weight configuration compatible with a particular defined mission could result in a reduction in repair action. As wing loading is often sensitive to Mach number, this may be another consideration which could effectively increase the damage tolerance of the structure. Also, the tension skin is likely to be the criterion of failure and this will have some extra margin because of fatigue design requirements.

2.2 Fuselage Structure

Front fuselages are generally over-strength as they are designed to minimum practicable sizes.

Centre fuselages are designed mainly by n.W. but tend to be redundant. Consideration of aircraft weight and 'g' could be of benefit just as for the wing structure.

Rear fuselages are designed by fin and tailplane loads which may possibly be reduced for wartime operations - see paragraphs 2.3 and 2.4 for more details.

2.3 Fin and Associated Structure

Fins are often designed to severe manoeuvres arising from extreme control inputs. It may be possible to reduce the loads for the short flying time associated with battle damage on the grounds of probability, and indications from a limited study are that fin loads could be reduced to about 70% of the design values.

2.4 Tailplane and Associated Structure

The general design cases for tailplane structures are response cases arising from adverse stick movements. These may be considered to be too severe for a limited number of operations, where more realistic high 'g' overshoots could result in a reduction in tail loads. A limited study has shown that a reduction to about 80% of the design value is possible.

To summarise, the Service engineers should have an understanding of the way that various sortie options for wartime operations could affect the levels of allowable damage. There will also be a difference in damage tolerance between the various major structural components.

3. DAMAGE CONTAINING SHARP-EDGED CRACKS

It would seem reasonable to assume that damage to structural skins caused by projectiles will contain sharp-edged cracks around the periphery. We do not have sufficient test evidence to show that such cracks should be treated in a different manner to fatigue cracks in terms of their effect on residual static strength, the analysis of which requires Fracture Mechanics' techniques, and this chapter of the report discusses the likely tolerance of structures to damage containing sharp-edged cracks. The failure criterion can be assumed to be the static failure of tension members, since this is the most significant failure mode for a damaged structure, also, it is reasonable to consider the load-carrying outer skins of the structure as being most vulnerable to damage. If the static failure is assumed to occur when the crack tip stress intensity exceeds the material fracture toughness K_c, the failure criterion can be written as:-

$$K_c = \sigma_c \sqrt{\frac{\pi D}{2}}$$

where: σ_c = crack stress at failure, and

D = maximum damage.

Residual static strength curves have been plotted for a range of light alloy materials to show that the conventional materials used in aircraft design behave in a reasonably similar manner - see Fig. 1

It is therefore possible to typify the performance of various parts of the structure, allowing for the differing thicknesses of the skin construction, and Figs. 2, 3 and 4 show the tolerance of typical wing, fuselage, fin and tailplane skins to sharp-edged damage in terms of stress against critical crack size. It is appreciated that variations in tolerance would occur if various aspects were taken into account, such as integral stiffeners with separate spars and ribs, but these curves give a good indication of the performance of typical light alloy skins with the presence of cracks.

3.1 Summary of Allowable Sharp-Edged Damage

3.1.1 Wing Structure (Fig. 2)

The allowable damage at stresses consistent with maximum manoeuvre g's is very small, compared to the size of damage which can be expected, even if the aircraft is restricted to 1/4 of the design envelope (for a ferry mission) it can be seen that the allowable damage is still only about 170 mm in the outer wing. It would seem, therefore, that some repair action will always be necessary, even if this is restricted to a simple cleaning-out operation to remove the cracks and sharp edges.

3.1.2 Fuselage (Fig. 3)

The aft end of the fuselage can be shown to be fairly tolerant to damage if the reduced fin and tail loads are justified. However, the highly-stressed centre portion does not come in this category, and would require to have the sharp-edges cleaned-out at the very least. The nose fuselage, with the possible exception of the cabin area, would appear to be highly damage-tolerant because of its low design stress levels (see para. 2.2).

3.1.3 Fin and Tailplane (Fig. 4)

Critical sizes of cracks to sustain the maximum design loads are smaller than the expected damage sizes, but as discussed in a previous paragraph, a re-consideration of the loading cases could improve the situation and show that these structures are fairly tolerant to damage containing sharp-edged cracks; they would not need as much repair as the wing for the same initial damage.

4. ANTICIPATED LEVELS OF DAMAGE WHICH WOULD REQUIRE NO REPAIR, OTHER THAN THE REMOVAL OF SHARP-EDGES

Certain regions of the structures are not very tolerant to sharp-edged damage, as outlined in the previous section, but it may be possible to recover a good deal of the strength simply by cleaning out these cracks.

This chapter discusses the results of studies to show the strength of typical areas of structure in an unrepaired state, but with all the sharp-edged damage removed.

Computer and hand analyses can be used to assess the effect of removing elements of the structure to simulate various levels of damage. By evaluating the resulting principal stresses and assessing the various failure modes, graphs of stress level (and hence allowable manoeuvre or 'g') against allowable damage size can be plotted. Figs. 5, 6 and 7 are examples of typical wing, fuselage, fin and tailplane allowable damage curves.

4.1 Summary of Allowable Cleaned-Out Damage

4.1.1 Wing Structure

If we make the assumption that the wing tension-skins are designed with a static reserve-factor of about 1.15 (consistent with some reduction in working stress to give an acceptable fatigue life), then Fig. 5 shows that, for full flight envelope clearance and the normally-accepted safety factors, the maximum allowable size of skin damage in terms of a cleaned-out hole requiring no further repair action is about 50 mm. Even if the aircraft is cleared to, say, 75% of its envelope, either by 'g' restriction or configuration or a limited Mach number, this allowable damage size only increases to 160 mm. Therefore, it would appear that, unless it is possible to limit the aircraft to below about 60% of its envelope, any significant damage sustained by a structurally-efficient wing torsion box would require repair action.

4.1.2 Fuselage Structure

If the stress levels in the rear fuselage are reduced in accordance with paras. 2.3 and 2.4, this will be tolerant to damage up to 250 mm in size.

The same can be said for the front fuselage, which may generally be assumed to work to relatively low stress levels.

The centre fuselage can be assumed to contain stresses similar to the wing structure and would therefore require repair action to be taken when the damage exceeds around 150 mm.

4.1.3 Fin and Tailplane Structure

If it is possible to agree on a new set of working loads for the limited period of wartime activity, as outlined in paras. 2.3 and 2.4, then the ensuing stress levels will allow cleaned-out damage of some 125 mm in size for the T/P and 200 mm for the fin.

It should be noted that, as fin and tailplane structures are to a large extent designed by asymmetric loading cases, any flight restrictions would be difficult to apply other than to impose gentle roll manoeuvres only.

The damage tolerance of these major structural components is summarised in Fig. 8.

5. BASIC REQUIREMENTS FOR REPAIR AT FORWARD AIR BASES

Consultation with the R.A.F. has led to the following requirements for structural repairs:-

(a) Repairs must be able to be applied as rapidly as possible, with a maximum time of 24 hours.

(b) They must be capable of being applied by personnel wearing combat suits.

(c) There may be no power sources available to operate tools or equipment, other than transportable cylinders of compressed air.

(d) External environmental conditions are to be anticipated as for North European Bases.

This means that any material used for repair patches should be able to be cut and formed very easily (if necessary) and any process, such as the application of adhesive, for example, must be both quick and simple to prepare and apply. The following section outlines some methods of repairing damaged, load-carrying, structural skins within the capabilities of a forward air base.

6. REPAIRS FOR STRUCTURAL SKINS

In this section, the discussion is directed towards the repair of load-carrying skin/stringer combinations.

Whilst realising that other structural members will need repair consideration, the skins are going to be the first point of contact and are more readily dealt with in the scope of this report.

6.1 Removal of Sharp-Edged Damage

The removal of sharp edges from around a damaged hole in a skin would seem to be a basic requirement as the first stage in restoring structures to either partial or full strength. A simple hand-tool is available which appears to be able to do the job very efficiently, but this requires compressed air to operate it; there may also be a problem in cutting the thicker skins on wing structures. Some experimental evidence needs to be obtained to establish the location of the ends of cracks in order that all sharp-edged damage can be removed without the need to use sophisticated techniques.

6.2 Application of Load-Carrying Repair Plates

Since structures containing a large amount of curvature are not usually heavily-loaded, this section can be discussed under two separate headings:-

(a) Highly-loaded regions with little curvature.

(b) Lesser-loaded regions with high curvature.

6.2.1 Highly-Loaded Regions with Little Curvature

This primarily covers repairs to wing skins but a similar approach can be applied to tailplane and fins.

The basic requirement for a repair is to restore the structure to full strength by replacing the damaged material. The object is, therefore, to choose a material which can be worked to the required shape and thickness and then attached to the structure using basic tools and facilities.

The use of carbon or glass-reinforced plastics has been considered and rejected in favour of metal sheets and plates, for the following reasons:-

- A cold-cure resin system would require support and access from each side of the plate, in order to work in the resin.
- A hot-cure system would require support whilst curing but there is also the disadvantage of having to apply heat.
- Pre-pregs. have no advantage over metal patches.

Because there is very little curvature, thick steel plates can be utilised and it may be possible to stock these in standard sizes to suit a range of damage sizes with the minimum of plate preparation.

If the plates are to be attached with bolts or rivets, this will require the time-consuming task of drilling the many large-sized holes. It is for this reason that the alternative method of bonding is to be recommended; the use of bonding will also allow the build-up of thickness from a series of thinner plates, as well as provide a gap-filling medium to accommodate slight curvature.

Out of the many cold-setting adhesives on the market, two appear to be good candidates for Battle Damage repairs, namely:-

- Versilok 506, which is an acrylic adhesive with a rapid cure and good gap-filling and tack properties, and
- Avdelbond E18, which is a rapid cure epoxy, also with good strength, tack and gap-filling properties.

The use of these adhesives would provide for a fairly quick application of repair plates; the only preparation being the removal of paint and the mixing of the adhesive. It will be necessary to add a few anti-peel rivets around the extremes of the plate, but these could be simple blind rivets.

Typical repair plate thicknesses are as follows, to cover wing, fin and tailplane damage:-

Component	Repair Plate Thickness for damage of:-		Overlap for Shear Attachment
	150 mm	300 mm	
Inner Wing	5 mm	7 mm	75 mm
Outer Wing	3 mm	4 mm	50 mm
Fin	3 mm	4 mm	50 mm
Tailplane	3 mm	4 mm	50 mm

6.2.2 Intermediate to Lightly-Loaded Regions with Significant Curvature

If metal repairs are to be used, consideration must be given to hand-forming for simplicity. With steel sheets, the maximum thickness which can be comfortably formed and cut with hand shears is about 1,0 mm.

Fortunately, the loading associated with these highly-curved regions is not as high as for the wing structure and the required thickness may be built-up by successive bonding on the 1,0 mm sheets.

Typical repair plate thicknesses are as follows, to cover front and rear fuselage damage:-

Component	Repair Plate Thickness for damage of:-		Overlap for Shear Attachment
	150 mm	300 mm	
Front Fuselage	1,4	2,0	50 mm
Centre Fuse.	3,0	5,0	50 mm
Rear Fuse.	2,0	3,0	50 mm

7. FORMAT OF A 'STRUCTURAL BATTLE DAMAGE MANUAL'

When an aircraft returns to base in a damaged condition, the Service Engineer will be required to assess the extent of the damage and make a judgement on whether the aircraft is structurally operational or whether repairs will be necessary in order that the aircraft can carry out a known, particular mission.

It is assumed that he has little knowledge of the internal loads on the structure and hence methods of calculating the load-carrying capability of a damaged structure; he will need some simple guide to assist him in making his assessments.

7.1 Sharp-Edged Damage

Para. 3 discusses the effects of sharp-edged damage and it would be a fairly simple task to translate this sort of study into fairly simple rules to cover all the major structural components.

7.2 Cleaned-Out Damage

Calculations can be performed, as discussed in para. 4, to enable graphs of 'allowable 'g' v/s damage size' to be plotted for all the major structural components or regions.

These can be presented in a very simple set of curves to cover the whole structure of an aircraft, and from these it will be fairly easy to decide upon either repair action or the flight envelope to which the aircraft can be cleared.

7.3 Proposed Method of Presentation

It will be necessary to present this information to the Service Engineer in the simplest possible manner, with the minimum of paperwork and necessity to read lengthy statements.

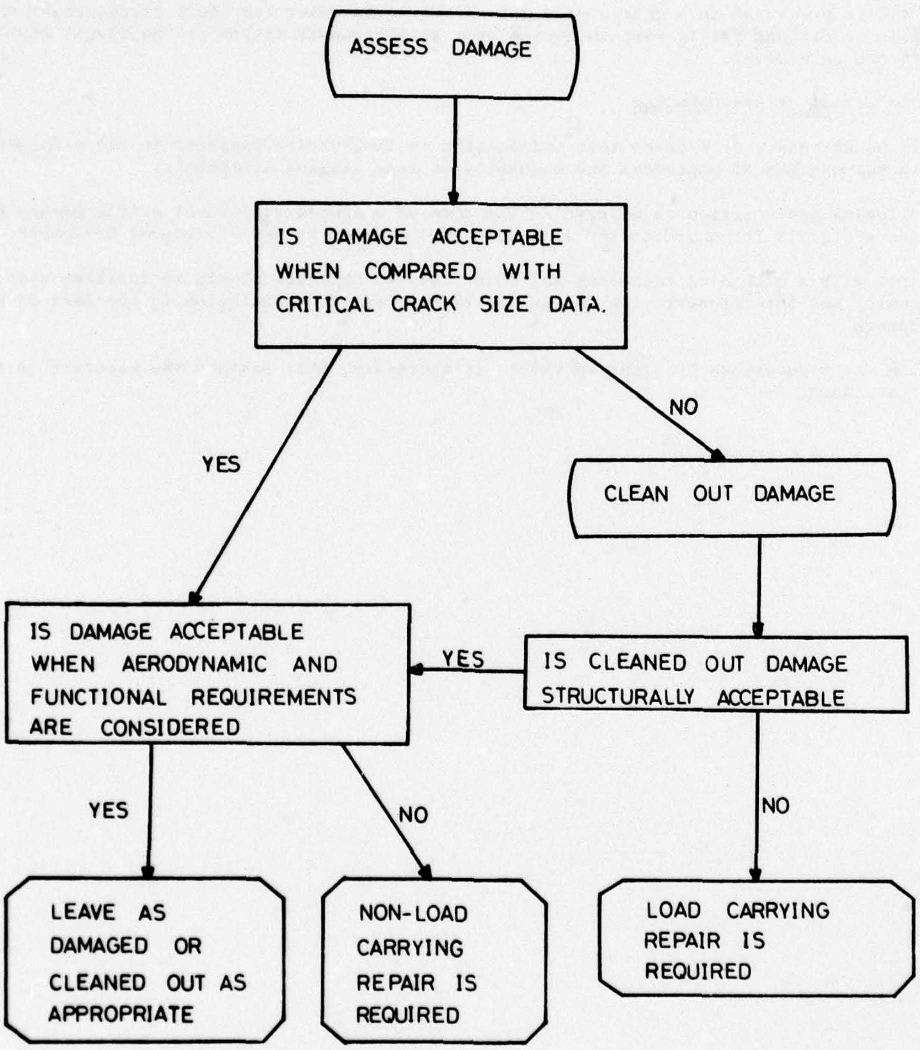
The following presentation is offered as the form of a simple Structural Battle Damage Manual which could be made available for any Military Aircraft after a study by the Structural Designers.

It starts with a method of reasoning which the Service Engineer should be familiar with, in the form of a flow chart, and then presents the results of the structural calculation in the form of graphs of allowable damage.

The final part describes the repairs which, if necessary, will restore the aircraft to full operational standard.

SUGGESTED FORMAT FOR A BATTLE DAMAGE MANUAL.

THE FIRST STAGE IS TO GO THROUGH THE FOLLOWING ASSESSMENT PROCEDURE.



REPAIR FLOW DIAGRAM SHOWING DECISION ROUTE NECESSARY TO DETERMINE CORRECT REPAIR ACTION.

FORMAT FOR A BATTLE DAMAGE MANUAL (CONTINUED)

IN ASSESSING THE ALLOWABLE DAMAGE OR REPAIR ACTION TO BE TAKEN, ONE HAS TO IDENTIFY THE RELEVANT STRUCTURAL REGION AND OBTAIN THE APPROPRIATE SECTION OF THE MANUAL FROM THE KEY DIAGRAM (AS BELOW).

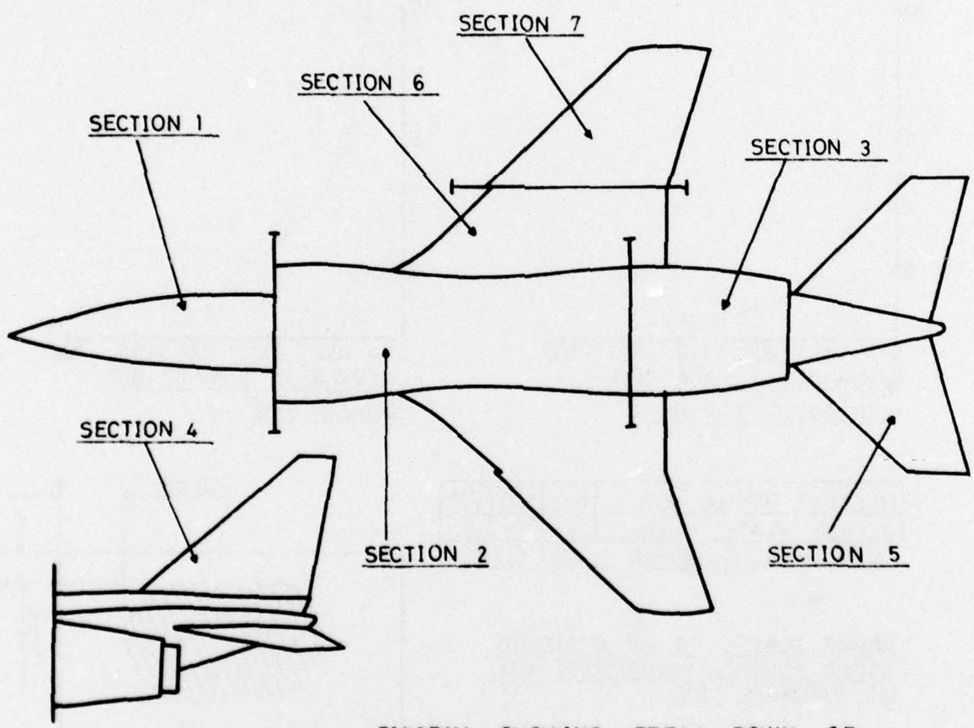
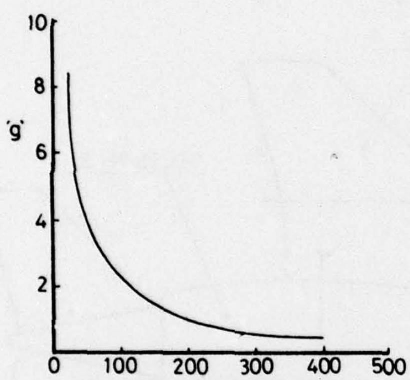


DIAGRAM SHOWING BREAK DOWN OF AIRFRAME INTO MAJOR REPAIR SECTIONS.

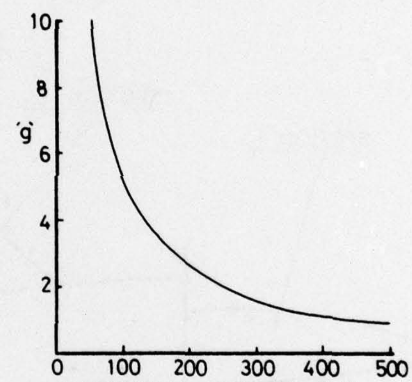
FORMAT FOR A BATTLE DAMAGE MANUAL (CONTINUED).

A TYPICAL SECTION WILL CONTAIN THE FOLLOWING INFORMATION FROM WHICH IT CAN BE DETERMINED IF REPAIR ACTION IS NECESSARY AND THEN THE SORT OF REPAIR.

A TYPICAL SECTION WILL CONTAIN THE FOLLOWING DATA.



ALLOWABLE DAMAGE SIZE CONTAINING CRACKS.

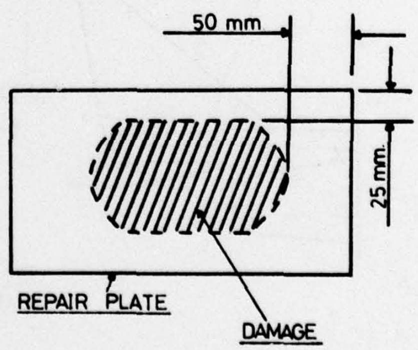


ALLOWABLE CLEANED-OUT DAMAGE SIZE.

MAXIMUM DAMAGE SIZE	150	300	450
REPAIR PLATE t mm	5	7	9

TABLE OF STEEL REPAIR PLATE SIZES.

REPAIR PLATES TO BE ATTATCHED USING ADHESIVE AVDELBOND E18 OR VERSILOK 506



8. CONCLUSIONS

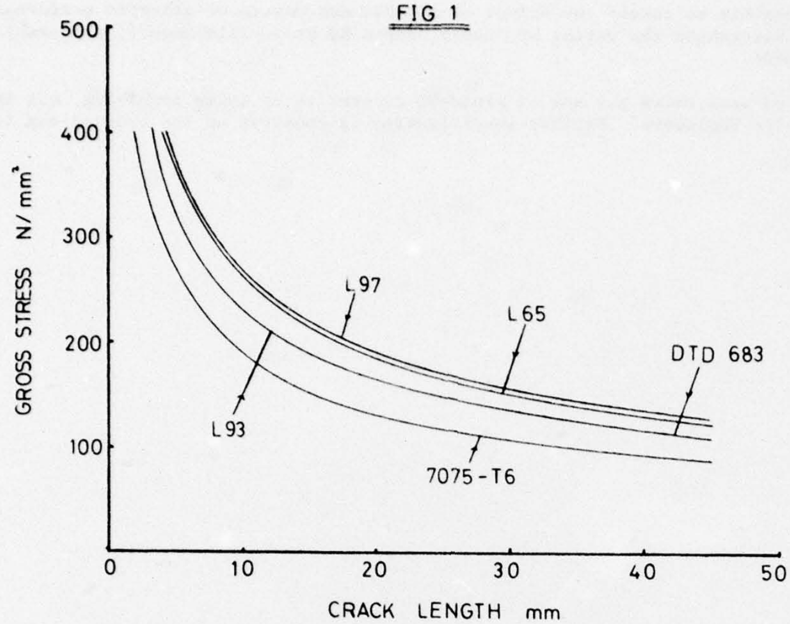
To enable the Service Engineers to be prepared for Battle Damage situations, the designers will have to prepare a simple information manual for each aircraft type. A suggested format for such a manual is outlined in para. 7. A limited study has shown that structures are not likely to be tolerant to sharp-edged damage, especially wing and centre fuselage structures. Attention should be paid to the location of, and removal of, this sort of damage since this would appear to be the very minimum repair action.

Although it is possible to assess the effect of cleaned-out damage on aircraft performance, it will be necessary to know beforehand the extent of damage caused by projectile impact, preferably whilst the structure is under load.

A limited amount of work shows the use of glued-on patches to be quite promising, but these should be developed by the Service Engineers. Further investigation is required on the cutting and forming of repair patches.

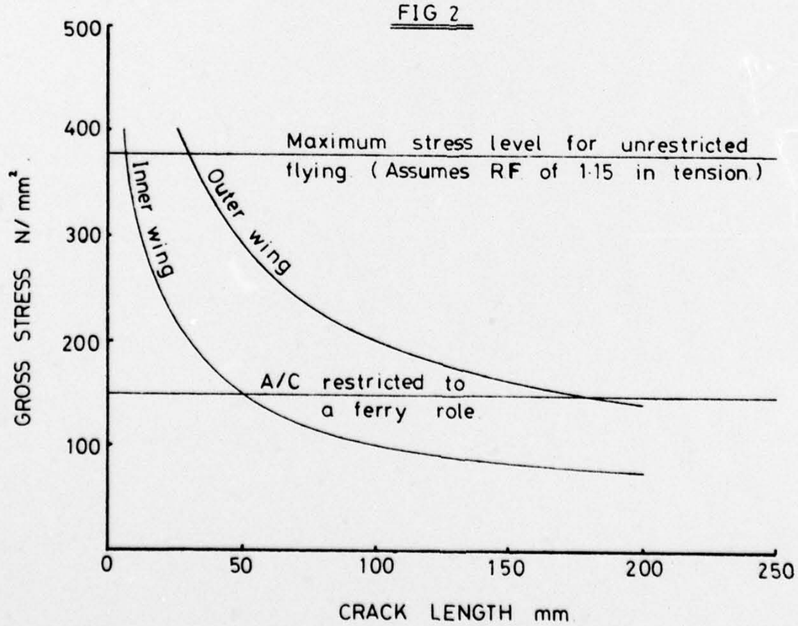
COMPARISON OF THE CRACK SENSITIVITY OF LIGHT ALLOYS UNDER PLANE STRAIN CONDITIONS USING CENTRE CRACK MODEL.

FIG 1



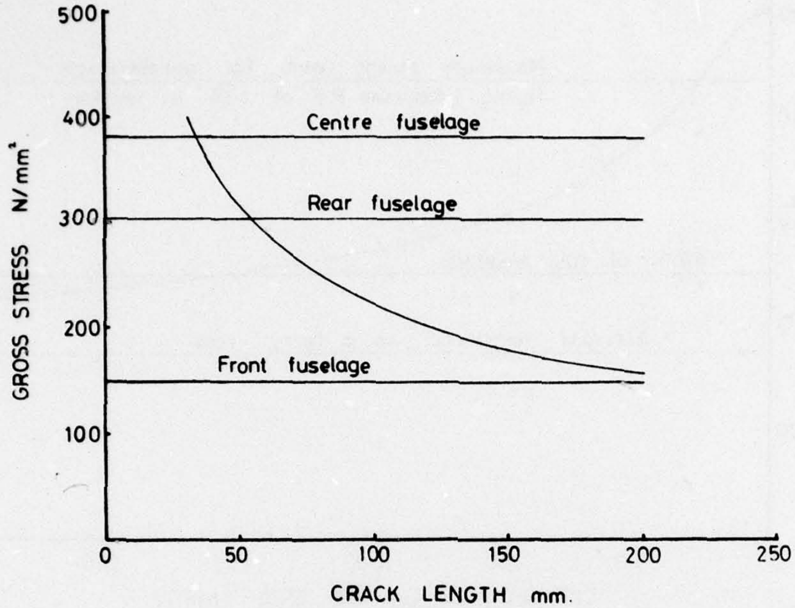
DAMAGE TOLERANCE OF A TYPICAL WING STRUCTURE ASSUMING SHARP-EDGED DAMAGE

FIG 2



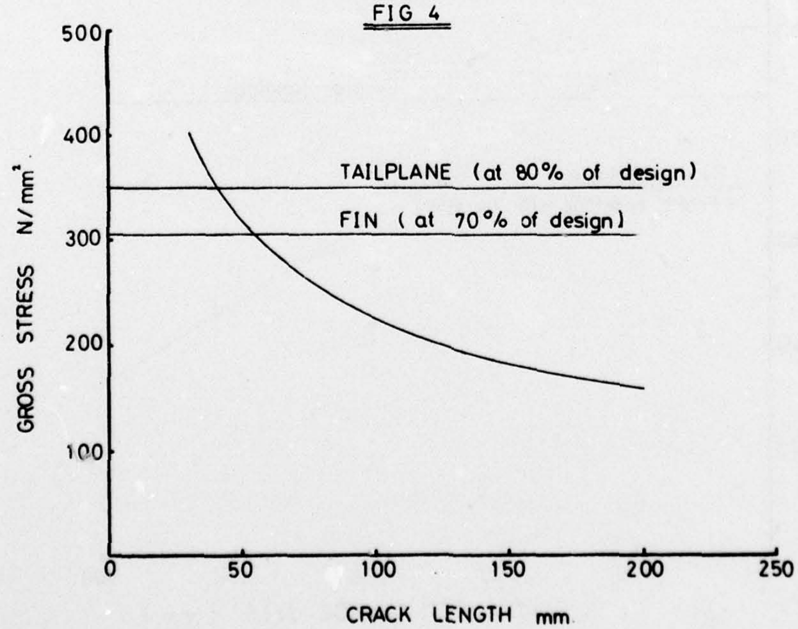
DAMAGE TOLERANCE OF A TYPICAL FUSELAGE STRUCTURE ASSUMING SHARP-EDGED DAMAGE.

FIG 3



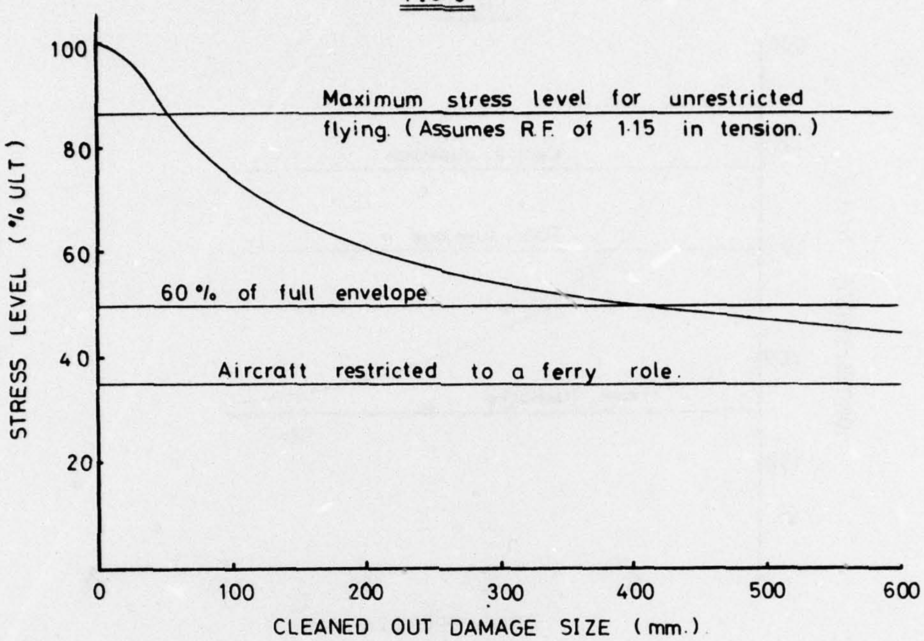
DAMAGE TOLERANCE OF TYPICAL FIN AND TAILPLANE STRUCTURES ASSUMING SHARP-EDGED DAMAGE.

FIG 4



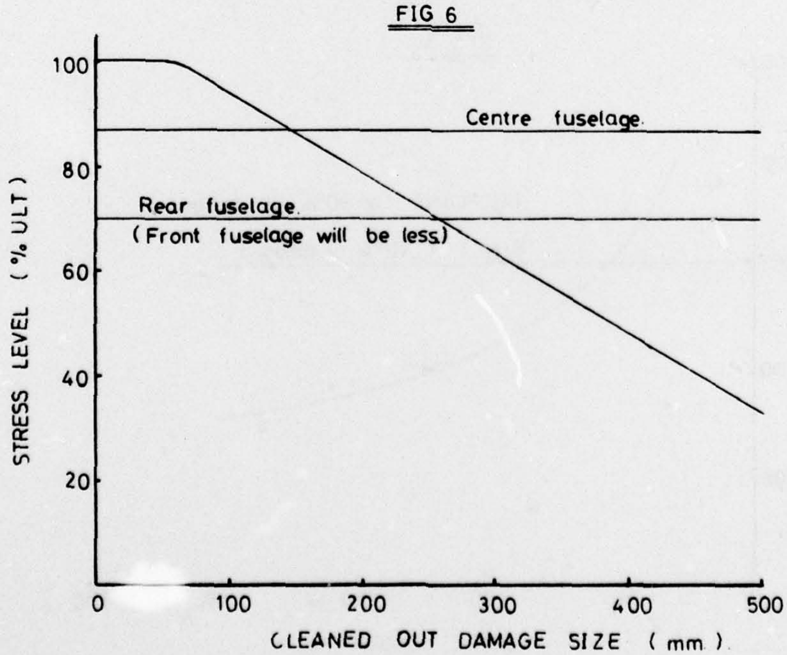
DAMAGE TOLERANCE OF A TYPICAL WING STRUCTURE WITH SHARP EDGES REMOVED FROM THE DAMAGED AREA.

FIG 5



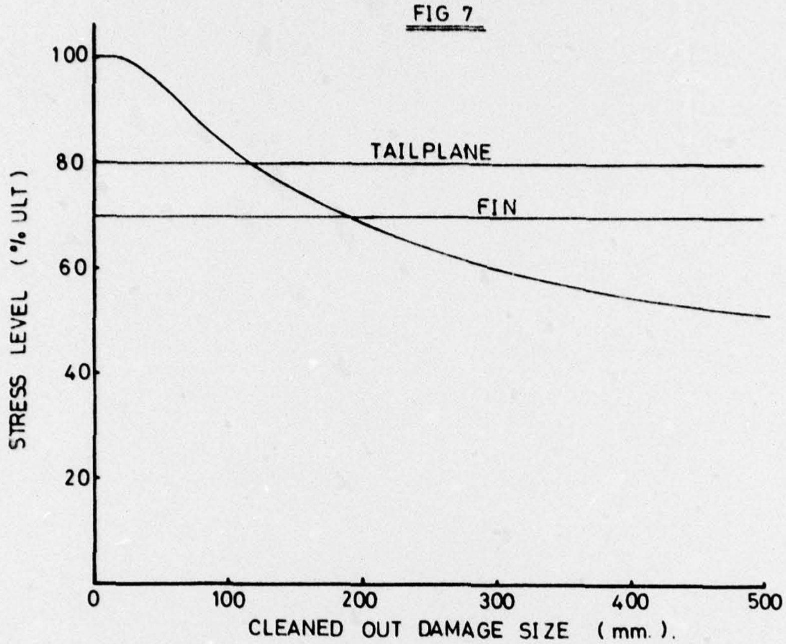
DAMAGE TOLERANCE OF A TYPICAL FUSELAGE STRUCTURE WITH SHARP EDGES REMOVED FROM THE DAMAGED AREA

FIG 6



DAMAGE TOLERANCE OF TYPICAL FIN AND TAILPLANE STRUCTURES WITH THE SHARP EDGES REMOVED FROM THE DAMAGED AREA.

FIG 7



SUMMARY OF THE DAMAGE TOLERANCE OF TYPICAL AIRCRAFT STRUCTURE.

FIG 8

COMPONENT	REMARKS
WING	ALMOST CERTAINLY WILL REQUIRE REPAIR ACTION UNLESS RESTRICTED TO < 60% OF ENVELOPE.
FRONT FUSELAGE	TOLERANT TO DAMAGE UP TO ABOUT 250 mm.
CENTRE FUSELAGE	TOLERANT TO DAMAGE UP TO ABOUT 150 mm..
REAR FUSELAGE	TOLERANT TO DAMAGE UP TO ABOUT 250 mm..
FIN	TOLERANT TO DAMAGE UP TO 200 mm..
TAILPLANE	TOLERANT TO DAMAGE UP TO 125 mm..

AIMS AND PROGRESS OF A BATTLE DAMAGE REPAIR CAPABILITY IN THE ROYAL AIR FORCE

by

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SUMMARY

This paper discusses the background to the RAF's decision to develop a capability to rapidly repair aircraft that have been damaged in combat, the likely damage expected and the progress made so far. It discusses future work and the features of aircraft design which would simplify Battle Damage Repair (BDR).

INTRODUCTION

During the last World War aircraft combat or battle damage was a regular occurrence and repair procedures and facilities were developed to cope with it. When, after the last war NATO adopted the nuclear trip wire strategy weapons were to be delivered irrespective of aircraft losses, and an aircraft's condition on its return - if it returned at all - was of little consequence. Therefore there was no need for a wartime repair organisation and our aircraft repair facilities became orientated to peacetime arisings only. When NATO's strategy changed in 1967 to one of flexible response the envisaged use of air power also changed. Aircraft would operate in close support and interdiction roles at high flying rates in which they could sustain damage that might not be catastrophic, and the aircraft could return, perhaps away from base, requiring rapid repair using whatever facilities were available. This is of course completely contrary to our peacetime practices and procedures and the damage can be expected to bear no resemblance to our peacetime experience which has been geared to maintaining a long operational life for aircraft. Assessment and repair is also complicated by the design of modern aircraft which have had to meet more demanding performance requirements, which in turn have led to the introduction of very high strength materials with low resistance to crack propagation; of new computer assisted stress analysis which pares away surplus structure; of complex avionic systems and of new production techniques all resulting in weapon systems that will be less tolerant to combat damage. Furthermore in peacetime, structural repair schemes are individually tailored by the design authorities to restore the full static strength and adequate fatigue and corrosion life with little regard to the time and manpower utilised whilst the majority of mechanical and avionic system repairs are by replacement with a pre-stocked or robbed item. Except for component replacement and robbing such procedures are incompatible with the war scenario currently adopted by NATO.

2. We have no doubt that if our operational effectiveness is to be maintained, aircraft damaged in battle will have to be quickly repaired for further missions. This can be illustrated by a preliminary assessment in the USA (Reference 1) of the effect of battle damage and its repair on the possible sorties of 2 A-10 squadrons, that is 48 aircraft operating in Central Europe. Although the A-10 is specifically designed to tolerate damage and be easily repairable, if an attrition rate of 3% and an associated damage rate of 13% are assumed, then unless a good repair capability exists 177 sorties will be lost over a 10 day period from the 777 that would be theoretically available. Assuming that 50% of the damaged aircraft can be repaired in 18 hours, and 50% in 6 hours, the sorties lost can be reduced to 63, so that 114 more sorties are available. If higher rates are assumed such as an attrition rate of 5% and a damage rate of 22%, even more dramatic numbers of mission denials occur. In these two cases we are talking of having to repair about 12 aircraft a day. This indicates the size of the task facing us, and it is unlikely that our peacetime resources could operate on this scale. Analysis of historic combat data including World War 2 suggests that 2 to 4 aircraft will return damaged for every aircraft lost and this proportion has been reasonably constant for all subsequent conflicts. We have therefore come to the conclusion that we have an overwhelming need to create a really effective BDR capability as quickly as possible.

TYPICAL DAMAGE

3. Our studies advise that the potentially repairable damage will primarily be that caused by multiple small projectiles or fragments which are generated by most proximity bursting air-to-air guided weapons and surface-to-air missiles, by small arms fire and by high explosive shell. Similar damage may also be produced by high explosive warheads and bombs which might be expected to be used against aircraft unprotected on the ground. The fragments can be expected to be travelling very fast and their distribution and number will depend on the orientation and stand-off of the weapon burst. The fragments will have the capability of penetrating deep into the aircraft, punching holes in the skin and structure and damaging system components encountered in their passage. In addition small contact fused high explosive shells will generate a small volume of blast damage in the immediate vicinity of their burst point giving external skin damage in addition to internal

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system damage. It is also likely that accidental damage will increase because of intensive operations in a dangerous and abnormal environment by tired personnel. For example it is expected that airfield lighting will be degraded in war and that the dangers of collision between aircraft and ground facilities will increase. Furthermore damage could occur from operating in a damaged environment of cratered runways and taxiways, FOD brought about by increased debris, nuclear or chemical attack, and possibly from weapon fire by friendly but confused forces.

CURRENT ACTIVITIES

4. Having set the scene I would now like to describe our current activities. Over the last few years we have attempted to create what we have called an 'Interim BDR Capability' at negligible cost for some of our combat aircraft. We have concentrated on these aircraft and expect the results to read - across to our other operational types. This capability has been primarily developed through service (RAF) resources with some assistance from our aircraft industry. RAF Abingdon and 431 MU have developed some elementary rapid repair techniques for structures and systems using hand tools and conventional materials normally available on RAF stations. In parallel with this work we are investigating all available methods of mechanical and electrical system repair, including non-aerospace methods which could be an application to the repair of battle-damaged systems. Our aim is to develop in-situ fabrication or repair techniques capable of being used with limited access.

5. Besides this work on simple repairs the Air Staff have prepared lists which describe guidelines for the acceptable degradation of systems that will still allow the aircraft to retain a full operational capability, a limited operational capability which will be specified and a strike or ferry capability. There will be large numbers of systems, electrical and mechanical, that can be unserviceable or damaged and yet still permit the aircraft to fly its full operational envelope. It must be said that the risks of losing the system completely on the next mission rises in these circumstances, but this could be acceptable.

6. All of the information and guidelines on acceptable degradation and repair schemes and techniques are being gathered together into Battle Damage Manuals, one for each of the aircraft types, and these will be continually updated as more information becomes available. The tools and materials required to support the repairs have been identified by the Engineering Staffs and they are being assembled in BDR Kits to be held in the front-line. There is also a great deal of enthusiasm and initiative being applied in the service to the creation of a capability for the remainder of our operational aircraft types and we plan to start developing these activities shortly. Ultimately, there will be a Battle Damage Manual for each aircraft type containing specific-to-type information on assessment and repair, and a general manual giving specific trade information. The development of this Interim Capability has highlighted areas which will require special consideration in the further development of a Complete Capability.

7. Damage Assessment. For example, a quick, accurate and complete assessment of damage will be a vital requirement of a wartime repair organisation, but few personnel have experienced battle damage. The results of poor assessment are obvious - they could lead to the unnecessary loss of an aircraft and waste the time that has been spent on an inadequate repair. When an aircraft returns with damage the pilot's debrief will provide a good assessment of the aircraft and possibly a guide to its operational capability, but its return to base does not necessarily indicate that it is fit for a further mission. The damage still requires assessment to ensure the aircraft can operate as a weapon system and will withstand the greater loads that a full fuel and weapons load will impose. Aircraft damaged on the ground will present an even greater problem because a pilot's debrief will not be available. We can expect damage to be in areas that are inaccessible in peacetime so it may be necessary to cut structure away to allow an assessment of system damage to be made, and even more to gain access for repair. We therefore require guidelines and inspection tools which will assist the assessor to make the correct repair decision. This decision will be influenced by how desperate the situation, the access required, the resources available, the time available, the requirements for the next mission and the following ground rules:

a. What is the extent of the damage and what effect does it have on airworthiness and the weapon system required?

b. Can the damage be tolerated for the next mission?

c. What operational penalty results from not performing a repair?

d. If a repair is necessary, which repair requires least resources and is quickest?

e. How long will the repair take?

The guidelines and information required to make this decision are not available yet, but they will be developed and provided in the Battle Damage Manual. Sufficient to say that an assessor is going to require a much deeper knowledge of his aircraft and its engineering than any tradesman is expected to have in peacetime and his responsibility, in war, is going to be great.

FUTURE PROGRAMME

8. Repairs and Standards of Repairs. The standard of repairs and the reduction of performance, operational capability and airworthiness that would be acceptable in war is difficult to define since it vitally depends on the operational situation. Our aim will be to restore the aircraft to its pre-damaged condition, in terms of strength and correct functioning, and our peacetime planning will be based on this. The restoration of peacetime fatigue strength will not be a requirement. However, the minimum standard must be that the aircraft can fly its next mission and operate effectively as a weapon system. This does not necessarily mean that repairs should only last for the next sortie, we would like repairs to restore sufficient integrity to last for as many sorties as are likely to be flown. Therefore the engineer-on-the-spot requires advice on the effect of damage, especially structural damage, on the integrity of the aircraft. We propose to involve our Design Authorities in studies of the effect of structural damage and present the information in our Battle Damage Manual in a form that can be easily understood and applied. We also need to continue the development of repair methods including the use of unconventional materials. Simple repair schemes and techniques are required that can be used at forward operating bases and in shelters where power supplies and facilities may be limited. Repairs will certainly need to be completed within a matter of hours with the maximum allowed unlikely to exceed 24 hours. We aim that repair materials and techniques should be standardised across our fleet to simplify the repair of diverted aircraft and to minimise provisioning problems and cost of development.

9. Resources. A further product of our work so far is the need to determine our resource requirements in terms of men, materials and spares, and studies have started on building and operating a mathematical model of BDR activities.

10. Training. Training is a great problem, for although we may be able to give training in wartime practices during peacetime, it will be difficult to give experience of a wartime discipline that will need to be flexible and require initiative and imagination. It is also important that our tradesman do not mix wartime and peacetime practices. A far greater awareness of battle damage repair requirements in terms of skill and outlook is needed if we are to successfully change from peacetime to wartime conditions.

FUTURE PROJECTS

11. One of the major problems that we are encountering in improving our battle damage repair capability is that insufficient attention has been paid during aircraft design in the past to the concepts of vulnerability, survivability and rapid repair. Redundancy is one way of reducing vulnerability and we do have this in important mechanical and electrical systems, but the reason for duplication and redundancy in these areas has been flight safety. Future aircraft must be designed to retain their airworthiness and ability to carry out operations after damage. They should be capable of returning to their bases in a damaged condition and be rapidly repaired or cannibalised so that we retain the maximum effective force size in the circumstances. We would therefore like to see materials selected for their tolerance to damage, toughness and suitability for speedy repair. Repair by replacement would be a major design philosophy for BDR. Structural modules which could be readily disconnected and replaced would increase the repairability of aircraft and could produce a robust structure that would be more tolerant of battle damage because of the number of joints. Our experience with the Harrier wing and the introduction of the modular engine suggests that the concept can be engineered and is not excessive in weight. Coupled with modular construction would be a requirement for interchangeability of parts, while minimising the number of handed components would reduce holdings and provisioning costs for BDR. Certain areas and components, including pilots, are more critical to airworthiness than others, and these should be identified at an early stage of design and receive priority of protection whether by armour or shielding by other less vital components. Furthermore the provision of access, or means of access, to all parts of the structure would simplify assessment of damage and repair.

12. Invariably, adoption of these concepts will involve trade-offs against performance and weight but the time has come when we must realise that performance may be quite seriously degraded if the optimum compromise is to be reached for an effective war machine which will also last for 20 years in peacetime.

CONCLUSION

13. In this paper I have discussed the background to the RAF's decision to develop a capability to rapidly repair aircraft that have been damaged in combat, the likely damage that we expect and the progress that we have made so far. Our aim is to minimise the amount of repairs carried out, but we still require repairs, practices and procedures that will be alien to our safety conscious, peacetime air force. We plan to issue guidelines in the form of a Battle Damage Manual for each operational aircraft type to assist in arriving at the correct repair decisions. However the responsiblity for assessment and repair will of course rest firmly and squarely on the personnel on-the-spot, both operators and engineers, who will be required to show skill, ingenuity and the ability to improvise.

14. Finally, it will be apparent that the development of a BDR capability is very much an on-going activity. We are making progress but we have many problems to solve and much more work to do in order to develop a meaningful capability for all of our operational aircraft types.

15. I have confined myself today to discussing the repair of battle damaged aircraft, but there are other constituents of the complete weapon system such as ground equipment, mechanical transport, communications and ground signals, and airfield aids and our aircraft operations would of course be severely limited if we were to attempt to operate without them. We are developing BDR capabilities for them as well.

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1. Paper P-1205 The Impact of Battle Damage on A-10 Availability and Sortie Rate - Institute for Defence Analyses Systems Evaluation Division.

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14. Abstract

The tolerance of the structure to various threats and the probability of the aircraft surviving the impact, completing the mission and returning safely to base is only part of the problem of maintaining an adequate defence capability. An aircraft is still "lost" as an effective part of the air force if it proves impossible to repair the damage quickly, particularly in the context of a short duration conflict. Vitally important are the methods of rapid inspection and assessment of the damage to determine the extent of repair required or if repair may safely be deferred. Thus the total number of aircraft required to meet a given military situation is determined at least in part by their combat damage tolerance and repair characteristics; improvements in these characteristics can produce real reductions in defence costs. The Structures and Materials Panel of AGARD reviewed these questions at its meeting in April 1978. Three papers were presented, and are reproduced here, giving an overview of the present situation and directing attention to the areas most needing further work.

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